Subgrid-Scale Parameterization in 3-D Models: The Role of Turbulent Mixing

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LONG-TERM GOALS

The long-term goal of this effort is to help improve turbulent mixing parameterization in 3-D numerical ocean circulation models used for studying the oceans, and in operational centers, for nowcasting/forecasting the oceanic state.

OBJECTIVES

The principal objective of this research is to help improve second moment closure (SCM) based ocean mixed layer (OML) models that are in current (and potential future) use in Navy community and operational ocean circulation models.

APPROACH

Extensive research over the past three decades has established second moment closure as a reasonable compromise between resource-intensive techniques such as large eddy simulations (LES) and simple bulk mixed layer models (for example, *Large et al.,* 1994). The SMC approach in its most practical form reduces to a two-equation model of turbulence, with prognostic equations for the turbulent kinetic energy (TKE) and the turbulence length scale (TLS), and algebraic expressions for the mixing coefficients (*Mellor and Yamada*, 1982; *Galperin et al.,* 1988; *Kantha and Clayson* 1994, 2000). These so-called algebraic stress closure models have become the mainstay of the US Navy operational ocean and atmosphere forecast models, for example the Shallow Water Analysis and Forecast System (SWAFS) run routinely at NAVOCEANO and Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) run at FNMOC, as well as many civilian operational (NOAA NCEP) and research (NCAR WRF) forecast systems.

However, three decades of research and over a decade of operational use have exposed some shortcomings of the current SMC-based OML models. For example, the popular Mellor-Yamada (MY) OML models in Navy operational use, have a tendency to under predict mixing and hence overestimate upper layer currents and SST. The most glaring conceptual weakness is the one related to the prescription of the turbulence length scale. MY models use an *ad-hoc* wall correction to their TLS equation (Mellor and Yamada 1982), whereas the k-ε (TKE and its dissipation rate) model used extensively by the European community (for example, *Rodi,* 1987) exhibits disturbing singular behavior in parts of the parameter space (*Burchard* and *Deleersnijder,* 2001). Another drawback is the local nature of the closure that does not work well under free convection conditions. Yet another one is ignoring the very important influence of surface gravity waves on mixing in the upper ocean. None of the Navy community ocean models such as ROMS/TOMS, NCOM and HYCOM incorporate completely surface wave effects; neither do they account for non-local effects under convection.

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Observational data to compare with turbulence models are scarce. Microstructure measurements have not become a routine staple of oceanographic measurements as CTD casts have been for decades. This has led us to make microstructure measurements during NURC/NRL 2006 DART cruises in the Adriatic Sea, and LASIE 2007 (Ligurian Air-Sea Interaction Experiment) in the Ligurian Sea. We have taken part in the DART 06A and 06B cruises in March and August of 2006, and been Scientist in Charge for the LASIE 2007 experiment on board the Urania R/V, collecting turbulence data using a microstructure profiler. See *Prandke* (2005) and *Prandke et al.* (2000) for details of the microstructure profiler used.

WORK COMPLETED

We have proceeded in the analysis of acquired microstructure data collected during the DART cruises (see *Carniel et al.* 2006 for details) and made comparisons with modeled dissipation rate and diffusivity from ROMS/TOMS model. Moreover, new turbulence data have been acquired during the LASIE 2007 Cruise in the Ligurian Sea, where the PO has coordinated a joint effort together with two other R/V acting as Scientist in Charge.

First comparisons between acquired data and model results have been obtained. Figure 1 shows an example of further analysis of the measurements made during the March 2006 DART06A cruise. Layered density structure most likely due to double-diffusive convection resulting from cold fresh water masses over warm salty ones can be seen in the buoyancy frequency and χ profiles.

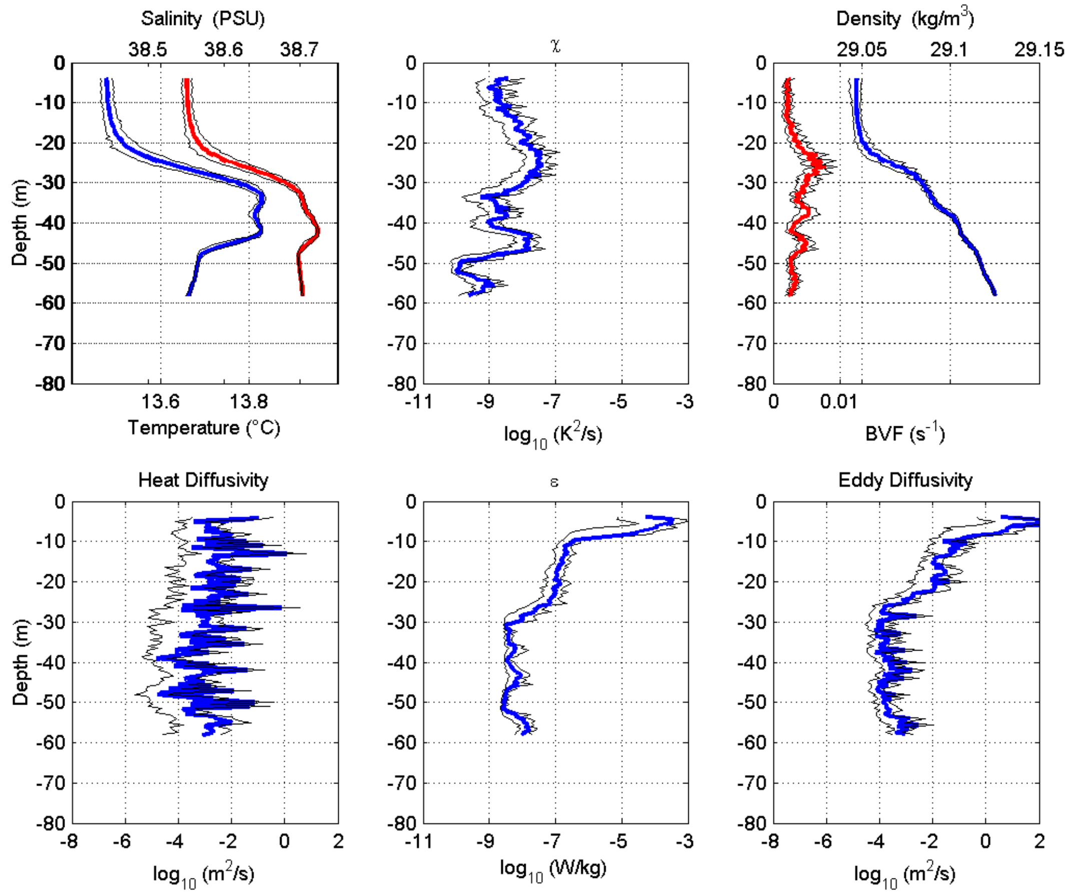

Figure 1. Staircase structures in the water column at Section-3 during DART06-A Cruise. The water column depth is 27 m. Note the enhanced dissipation rate of thermal variance at the interface between well-mixed layers. Measurements were made on March 20, 2006. Upper panels: (a) temperature (°C) and salinity (PSU, red) in the water column, (b) temperature variance dissipation rate $\chi\vartheta$ (K2s-1), (c) density $\sigma\theta$ (Kg m-3, blue) and buoyancy frequency (s-1). Bottom panels: (d) heat diffusivity $K\vartheta$ (m2s-1), (e) TKE dissipation rate (W/Kg), (f) eddy diffusivity KM (m2s-1). Color lines are the average, the two thin black lines represent the bootstrap confidence limits.

Figure 2 shows the corresponding water masses depicted at different depths.

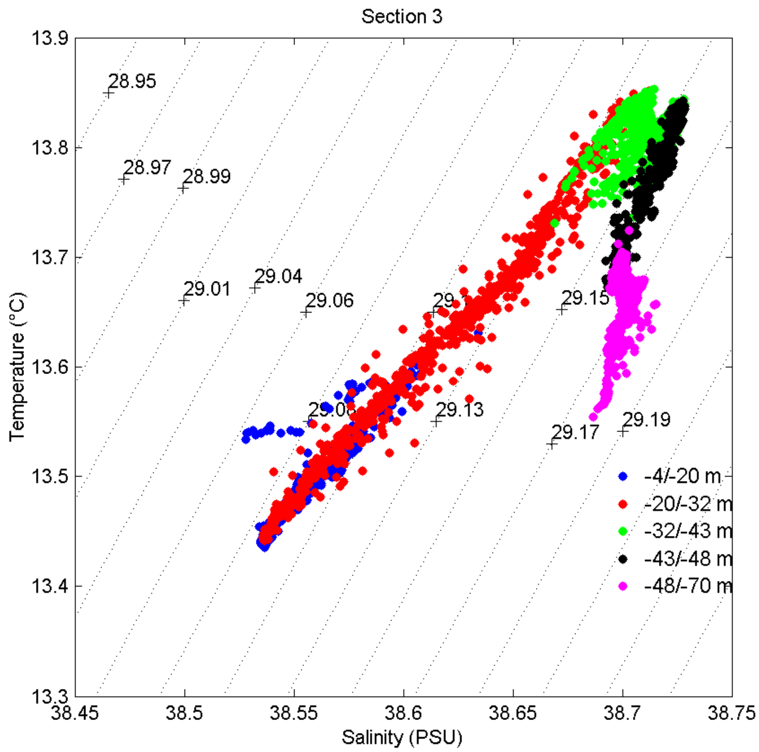

Figure 2. T/S diagrams for Section-3, with water masses depicted at different depths.

Water masses at Section-3 are characterized mainly by a slightly saltier (38.52-38.7 PSU) and much warmer (13.45-13.85 °C) water mass w.r.t. most of the water of the other measurements, thus originating a lighter (29.06-29.18 kg/m3), representing an off-shore, open ocean water.

For double diffusive convection with a temperature and salinity changes of ΔT and ΔS across the interface, and hence a density ratio $R_\rho = \dfrac{\alpha \Delta T}{\beta \Delta S}$ (α=0.216·10^{-3} °C^{-1} and β=0.77·10^{-3} PSU^{-1}), the values of momentum, salt and thermal diffusivities are (Marmorino and Caldwell, 1976):

$$K_M = K_S = \begin{cases} 0.15 R_\rho K_\theta & (if\ R_\rho < 0.5) \\ K_\theta (1.85 R_\rho - 0.85) & (if\ 0.5 \le R_\rho < 1.0) \end{cases} \tag{1}$$

$$K_\theta = 0.909 \nu \exp\left\{ 4.6 \cdot \exp\left[-0.54 \left(\frac{1 - R_\rho}{R_\rho} \right) \right] \right\}$$

where ν=1.5·10^{-6} m^{2}s^{-1} is the molecular kinematic viscosity of water.

For salt fingers,

$$K_M = K_S = \begin{cases} \left[1-\left(\dfrac{R_\rho - 1}{0.9}\right)^2\right]^3 \cdot 10^{-3} & (if\ 1.0 \le R_\rho < 1.9) \\ 0 & (if\ R_\rho < 1.) \end{cases}$$

$$K_\theta = 0.7 K_S \tag{2}$$

For the two interfaces at station GS2, ΔT= 0.67°C and ΔS= 0.33 PSU so that $R_\rho = 0.56$; according to Eq. (1), we have K_θ=7.1·10^{-4}, $K_S = K_M$ = 1.4·10^{-4} m^{2}s^{-1}. These values are consistent with the diffusivities presented in Kelly (1984) and while the peak values in measured K_θ are much higher, the average value for the water column is about 2·10^{-5} in rough agreement with the value cited above.

For the bottom salt finger interface of Section-3, ΔT = 0.12°C and ΔS = 0.03 PSU so that $R_\rho = 1.12$; therefore, according to Eq. 2), we have K_S= K_M= 9.4·10^{-4}, K_θ= 6.6·10^{-4} m^{2}s^{-1}. The values for K_θ and K_M in Fig. 4 are computed assuming conventional turbulence and hence:

$$K_M = \frac{R_f}{1-R_f}\frac{\varepsilon}{N^2} \approx 0.25\frac{\varepsilon}{N^2}$$

$$K_\theta = K_S = \frac{\chi_\theta}{2\left(\overline{\theta_z}\right)^2} \tag{3}$$

where R_f is the flux Richardson number (i.e. the efficiency of conversion of TKE into potential energy, ~0.2) and N is the buoyancy frequency. As can be seen in Figure 1, peak values are both roughly around 10^{-4} m^{2}s^{-1}.

Instead, if we use the relationship proposed by McDougall (1988) to compute the effective vertical eddy diffusivity of salt in salt fingers:

$$K_M = \left(\frac{R_\rho - 1}{1-f_R}\right)\frac{\varepsilon}{N^2}$$

$$K_\theta = \frac{\chi_\theta}{2\left(\overline{\theta_z}\right)^2}; K_S = \frac{R_\rho}{f_R}K_\theta \tag{4}$$

where f_R is the flux ratio. In this case, the values for K_M presented in Figure 1 would be considerably higher, since the coefficient of $\dfrac{R_\rho - 1}{1-f_R}$ is around 1, if we take a value of 0.9 for the flux ratio at $R_\rho = 1.12$ (however, note that there exist considerable uncertainty in extrapolating the flux ratio

measurements of Takao and Narusawa (1980) to values of R_ρ slightly higher than 1). If we use the second relationship in Eq. (4) the values would be similar to those of K_θ but 25% higher. Either way, the results are well within the confidence limits of the bootstrap analysis of the measured values.

RESULTS

When the turbulence is generated by both the momentum flux and a destabilizing buoyancy flux, the TKE dissipation rate ε in the mixed layer can be taken to be the sum of the rates due to shear-driven and buoyancy-driven turbulence.

The following expression for scaling can be used:

$$\begin{aligned} \varepsilon &= \varepsilon_c + \varepsilon_s \qquad z \le D \\ &= \varepsilon_i \qquad z > D \end{aligned} \tag{5}$$

where in the convective mixed layer we have

$$\begin{aligned} \varepsilon_c &= J_{b0} \qquad z = 0 \\ &= 0.39 J_{b0} \quad 0.1D \le z \le 0.9D \\ &= 0 \qquad z \ge D \end{aligned} \tag{6}$$

and in the wind-stress driven region

$$\begin{aligned} \varepsilon_s &= u_*^3 / (\kappa z) \qquad 0 \le z \le 0.3D \\ &= 3.33 u_*^3 / (\kappa D) \quad 0.3D < z \le D \\ &= 0 \qquad z > D \end{aligned} \tag{7}$$

Below the mixed layer depth D, the expression $\varepsilon_i = C_K L_T^2 N^3$ (9), resulting from assuming that the Ozmidov scale L_O is proportional to this overturn scale L_T , i.e. $L_O = c_0 L_T$, can be used.

Considerable effort has been expended in determining the value of c_0 (See *Thorpe* 2005 for a summary and *Dillon* 1982 for a lucid discussion of the Thorpe scale and related issues). Plots of the observed L_T versus L_o in the ocean show considerable scatter (*Osborne* 1980, *Dillon* 1982, *Wesson and Gregg* 1994, *Moum* 1996, *Peters et al.* 1988, *Ferron et al*. 1998, *Gargett* 1999, *Caldwell* 1983, *Galbraith and Kelly* 1996, *Fer et al.* 2004) typical of all microstructure measurements, and so the value of c_0 does involve some uncertainty. The scatter may very well be due to the noise and the resolution of the sensors, but the bin size used in determining L_T may also be an important factor. In *Wesson and Gregg* (1994) measurements, c_0 ranges between 0.25÷4.0, yielding a value of C_K between 0.0625÷16.

In order to further investigate the validity of the relationship expressed by $\varepsilon_i = C_K L_T^2 N^3$, the values of the Thorpe scale (i.e. the RMS of the Thorpe displacements) at different bins resolution (0.5 m, 1 m, 2 m and 5 m) were computed, using the full dataset available at B90 station, collected during the DART-

06B cruise, August 2006. Corresponding values for the proportionality constant c_0 were around 1., close to the lower range proposed by *Wasson and Gregg* (1994). The value of the proportionality factor appears to be dependent on the length of the bin considered and varying if computed at different depths, representative of different processes.

Figure 3 presents a log-log diagram of the values of the L_T *vs* L_O, computed following Eq. (9), for the 5 m bin example (average c_0=1.15).

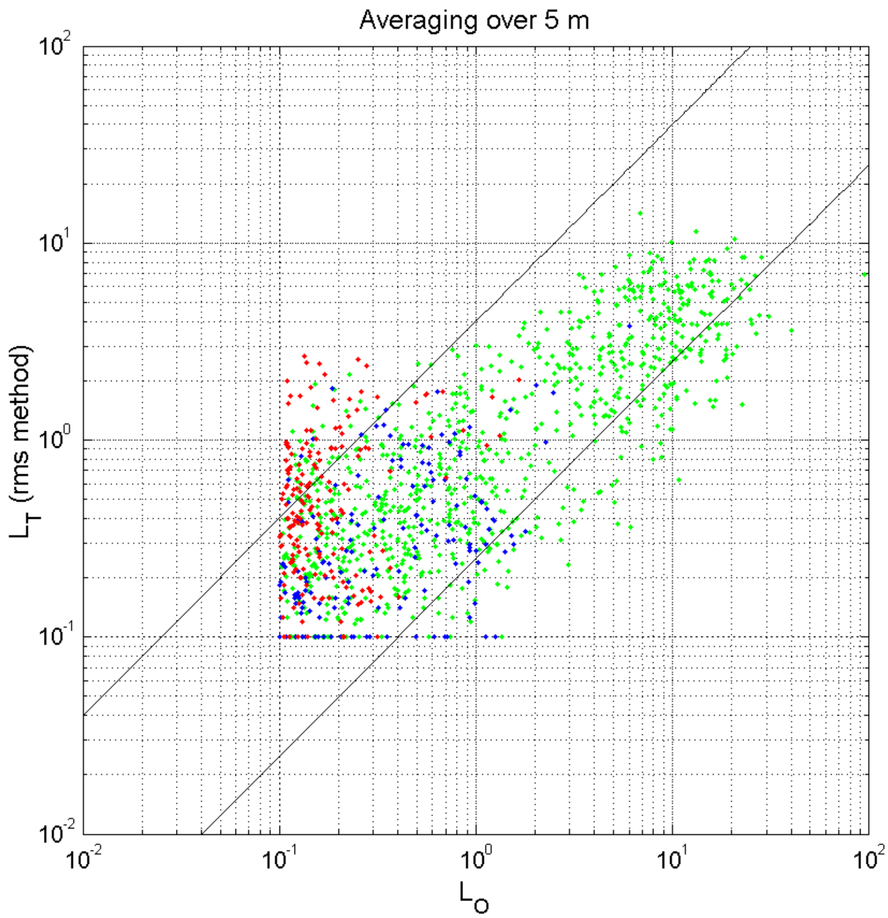

Figure 3. L_T and L_O values for B90 values, 5 m bin average.
The two black lines represent the L_T=4L_O (upper one) and L_T=1/4L_O

IMPACT/APPLICATIONS

Accurate depiction of many quantities of interest to worldwide naval operations, such as the upper layer temperature and currents, requires accurate simulation of turbulent mixing in the water column and accurate tidal forcing. Operationally, this contributes to better counter mine warfare capabilities through better and more accurate tracking of drifting objects such as floating mines. Other drifting materials such as spilled oil are also better tracked and counter measures made more effective. Other applications include search and rescue. Turbulence data collected under this project can help assess turbulence parameterization in OML models.

RELATED PROJECTS

1. Astronomical Tides and Turbulent Mixing in ROMS/TOMS (PI - L. Kantha) – N00014-06-1-0287. Started February 2006.

2. Improving the Skill of Ocean Mixed Layer Models (PI - L. Kantha) – N00014-05-1-0759. Ended June 2006.

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1. Carniel, S., L. Kantha, H. Prandke, M. Rixen, and J. Book (2007) Turbulence Measurements Across a Coastal Front in the Southern Adriatic Sea during Spring 2006. (under preparation).
2. Carniel, S., L. Kantha, H. Prandke, J. Chiggiato, and M. Sclavo (2007) Turbulence in the Upper Layers of the Southern Adriatic Sea Under Various Meteorological Conditions During Summer 2006. *J. Marine Systems.* (submitted).
3. Carniel, S., L. Kantha, H. Prandke and M. Sclavo (2007) Double-diffusive layers in the Adriatic Sea. *J. Marine Systems.* (submitted).